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On Aerial Infection

by C. Fluegge

Translated from Zeit. f. Hygiene, 25:179-224 (1897) by the Technical Library, Technical Information Division.

The conditions under which living germs pass from moist and dry surfaces into the air, as well as the transport of droplets or dust particles laden with germs by air currents, have not been studied thoroughly to date and have not been recognized to the extent demanded by the hygienic importance of this question.

Concerning the separation of germs, there is an irreconcilable divergence between the experimental results of Naegeli and Buchner on one hand, and those of Soyka on the other. Naegeli has clarified our concept of the behavior of dust-like components of the air in many respects by deducing the conditions for separation of dust-like elements from wet and dry surfaces, as well as for the floating and movement of elements in the air, from known physical facts and by explaining these mathematically. Specifically, he deduced that no germs are removed from the surface of germ-laden fluids by evaporation or even by strong winds, as long as there is no formation of waves and spray of the fluid which would throw fine droplets into the air 1/. Naegeli and Buchner 2/ have further tried to support these assertions by experiments, which, however, have been described only in a short, tentative report. They conducted air currents of 10 to 20 m per second through a U-tube filled with putrefying solutions and obtained no separation of germs, since a second U-tube connected to the first, containing a nutrient, remained sterile.

This result is opposed by Soyka's results who observed infection of an attached medium after passing an air current of 3 centimeters per second over a putrefying fluid. Even lower speeds sufficed to carry off germs from fluids and to infect exposed nutrient substrates.

1/ Naegeli. The Lower Fungi. Munich, 1877, page 107.

2/ Proceedings of the Bavarian Academy of Sciences. Munich, 7 June 1879. - Studies of lower fungi. Munich, 1882, page 124 fol.

The quarrel between Naegeli and Soyka has not ended. Death has recalled both researchers in short succession. Naegeli objected to Soyka principally because the admitted air had not been freed from accidentally present germs; insufficient attention was devoted to the filtering wad of cotton. Naegeli claims that the turbidity of nutrients in Soyka's tests was caused by these atmospheric organisms.

However, Naegeli's test arrangement itself was objectionable. The report that the test fluid was subjected to an air current of 10 and 20 m per second can only be interpreted to mean that the air would have passed through utilized tubes at this rate if air passage were unimpeded; after the inclusion of a cotton wad which was designed to filter off any germs contained in the admitted air, the speed must have been considerably lower, resulting in an air current of 1 to 2 m or less at the point where it touched the putrefying fluid. At least I was unable to achieve rates above 2.8 m upon passage of strong air currents through glass tubes of different widths, even behind a bacteria-fast cotton wad. Even this is possible only if forward movement of the stopper is prevented by a recess in the tube; otherwise the stopper is thrown out. If the rate is increased, the stopper is pressed against the recess to such a degree that it becomes impassable and the effect is not greater but smaller. Only if the cotton stopper is inserted in tubes of much bigger diameter, more air will pass; but the impermeability of such stoppers to bacteria is very doubtful. If Naegeli had really obtained rates of 10 to 20 m on the other side of the cotton stopper employed by him, it is likely that a spray of the putrefacted fluid and consequent infection had been produced. The difficulty of moving strong air currents across fluid surfaces apparently consisted in filtration of germs from the aspirated air. Since we have found a method of employing pure cultures of specific bacteria not present in the air, which makes it superfluous to treat the entering air with cotton stoppers and to render it sterile, it is possible to accelerate the current and to identify those which produce separation of germs from fluid surfaces.

There are only a few tests by Soyka which discuss the conditions under which germ-laden particles are torn away from dry surfaces and transferred to the air. Soyka allowed air to pass through a dust-laden powder made of putrefied blood; from there the air was conducted into a sterile nutrient solution. The air current transported germs already at a rate of 4.65 cm per second; even at 8 mm per second red particles of blood dust could be recognized in the lower portion of the conducting tube, which were not carried as far as the nutrient, however. When he passed air across and not through the blood dust, transportation of germs took place only at 11 cm per second.

The test arrangement used by Soyka is also vulnerable to Naegeli's objection. Moreover, the tests are insufficiently varied with respect to material and speed, and therefore cannot be considered valid.

A few years later Wernich [1] reported on tests involving separation and transport of atmospheric organisms. On the whole he confirms Naegeli's data; the attached sterilized nutrient solution was infected only when air bubbles passed through a fluid or when fermentation and foaming take place on the fluid, and fluid particles are scattered when the bubbles burst. In testing the transportability of bacterial dust, Wernich claims to have found that development on the new nutrient substrate takes place only when old nutrient is carried along. These and similar, obviously incorrect conclusions may be traced to errors in the test arrangement, which in those days could hardly be avoided, and to exclusive employment of very low speeds (air currents under 1 cm per second).

Studies made by Stern (this journal, vol. 7) in my institute several years ago offer a certain contrast to Soyka's results. Finest sterile dust impregnated with specific germs (spores of Bacillus megaterium) was deposited on different wooden plates, pieces of wall paper, canvas, woolen materials, etc., of equal size and subjected to air currents. These samples were then covered with fluid substrate in culture dishes and the resultant colonies were counted; the same was done with samples not exposed to the air currents. No constant difference could be noted between the two. A marked separation of dust particles therefore had not taken place, although the rates of air currents were as high as 2.1 and 2.5 m per second.

We have even less information about the conditions under which germ-laden droplets or dust particles move after placement in the atmosphere. Stern's tests merely indicate that almost all dust particles have settled after 1½ to 3 hours in completely calm indoor air, and that considerable movement of a part of the suspended germs takes place only upon very strong ventilation, that is, upon 6 to 7-fold renewal of air per hour. Such ventilation within a closed space suggests an air current of 10 to 20 or 30 mm per second, depending on the distance from vents.

It is desirable, of course, that we obtain more data on the speeds which move suspended droplets and dust particles of different type; that we know how the latter are distributed in calm air, in the ventilated room and in the open; and further, that we know which pathogens remain viable in the form of such particles and droplets transportable through the air, and which may then infect via the air. It is clear that knowledge of these conditions would considerably influence our concepts of the manner in which parasitic germs are disseminated.

1/ Virchow's Archiv, Vol. 79, 1880.

In the last 5 years I have made numerous studies of the processes discussed here, some of which gave entirely different results than I had expected and which have led me to conclude on the basis of subsequent tests that we must modify our concepts of the genesis of aerial infection and specifically of the role played by droplets and dust particles in the dissemination of infectious diseases.

I. STUDIES OF THE SEPARATION OF GERMS FROM MOIST AND DRY SURFACES

A portion of data relevant to these studies has already been reported by E. Hamburger in his inaugural dissertation (Breslau 1892); however, at that time we did not measure the rate of air currents precisely and had not varied the material sufficiently.

First of all we discontinued the method by which aspirated air is filtered by cotton, as used by earlier investigators. Instead we use exclusively pure cultures of Bacillus prodigiosus and Bacillus megaterium which were placed in sterile glass tubes or were used for impregnation of sterile soil or clothing, etc. The separated germs were either captured in a William tube (this journal, vol. 15, page 170) coated with levulose, whose contents were washed out and distributed on agar plates after the end of testing (about 80% of passing germs were captured in this manner); or the air was passed directly across plates or through tubes coated with agar, the latter especially whenever the quantitative recovery of all separated germs was not planned.

The bacterial content of aspirated air never had a disturbing effect. Tests were carried out in a calm room with avoidance of dust; relatively few foreign germs developed on the substrates and they did not interfere with observation of colonies of test bacteria, especially since the latter had been chosen with regard to their rapid and characteristic growth on the media utilized.

The air currents which could enter at the desired speed through this test arrangement which avoided cotton filters, were supplied partly from a water blower (construction by Danneberg and Quandt) which, however, produced too little air in connection with fairly narrow receivers, partly by a strong rubber balloon, but in the main by two large bellows operated by the feet whose air current was adjusted by placement of different weights (more than 20 kg for maximal flow).

The measurement of speeds was carried out with a Recknagel anemometer. If the currents no longer caused rotation at the diameter of the tube which admitted the anemometer, the measurement was made according to the quantity of air passing through a graduated gasometer during a certain time (1 minute). The separation from water surfaces was tested by filling a 2 cm wide glass tube with slightly upturned ends with suspensions of prodigiosus. The tube was then placed upright in a larger glass box and the bottom of the latter was covered with agar dishes. The outlet entering the glass tube from the bellows met the fluid surface at an angle of approximately 45 degrees. Under such conditions an air current of nearly 1 m per second already caused weak undulation on the surface, without, however, separating any germs. Separation commenced at a rate of about 4 m per second, which induced foaming of the fluid and atomization on the glass wall. In this case the plates showed hundreds of colonies after 15 minutes.

The tests were repeated with a modification that involves filling of 1/3 of the tube with a layer of sand and fine gravel and its saturation with a suspension of prodigiosus until small pools of fluid form on the uneven surface. In this case air currents of up to 1 m per second were unable to effect separation of germs. At about 4 m, small waves were formed on the smaller water surfaces which were drifting against the neighboring gravel and sand particles and were probably atomized here; the plates placed in the tube's opening were covered with colonies. The results were similar when air was passed over coarse fabrics which were impregnated with prodigiosus suspension until small pools of fluid collected on the surface.

According to these results, Naegeli is right when he claims that germs are not separated by evaporation or by air currents which pass across the unimpaired surface of the fluid. Fine droplets formed only upon forceful separation of the surface, and only these can transport germs. Formation of such droplets does not take place only in the extreme cases assumed by Naegeli, but occurs very frequently in nature and under practical conditions. An air current of 4 m per second, that is, a mild wind capable of moving leaves, found in the open during most of the year, is able to separate germ-laden droplets from water surfaces, e.g., from rain water pools, from wet leaves, etc. The extent of this separation is dependent on the velocity of the wind, on the angle at which it meets the fluid surface, and on the configuration of the marginal solid surfaces. Under normal conditions in the open, there will be very frequent transition of germs to the air in the form of liquid droplets, and not only in currents exceeding 20 m per second. This agrees with daily experience involving visible and perceptible sprays emanating from agitated water surfaces.

Under special conditions in the open, the mass of germ-laden droplets entering the air will be quite considerable; for instance near the ocean's surf, near water falls, mill wheels, the propellers and wheels of steamships, etc. However, a transfer of fine droplets from liquids to the air takes place also in a closed space, and this much more frequently than generally assumed. Small droplets which enter the air are formed upon pouring of one liquid into another, upon impingement of the droplet or a stream of fluid on a solid or liquid surface, during handling of wet laundry, during the mopping of floors, and especially during speaking, coughing, sneezing, etc.

In addition we must modify our current assumption that these droplets persist in the air only within short spaces and for very short periods of time. As will be demonstrated below, the most minimal of air currents can transport such droplets across great distances and may disseminate them into all parts of a living space and, naturally, also in the open. The sprayed droplets invariably include some so small that their suspension in the air is guaranteed for longer periods, until they finally settle on a solid surface or until the water evaporates. We must therefore expect, more than before, uptake of germs into the air in the form of droplets. An odd contrast to these observations and conclusions is offered by some results of studies on the bacterial content of the air, especially results obtained over the open sea. The air has been found to be sterile at sufficient distances from land, even on such days when high seas and strong winds undoubtedly filled the air with numerous droplets of ocean water which always contains organisms!

This contrast must be attributed to the methods used in bacteriological examinations. Daily experience teaches that persons exposed on deck to a strong wind will be covered with countless fine droplets on their clothing, face, glasses, etc. These droplets stirred up from the waves by the wind naturally contain bacteria, and one cannot speak of the sterility of ocean air and assume that no germs from the numerous germ-laden droplets suspended in the air have made contact with the body and the entrances to the respiratory tract.

If Fischer and others nevertheless found no germs 1/, it is due to the fact that they used Hesse's method of slow aspiration of air through a glass tube coated with gelatin. The entry aperture, with the exception of the small central hole, is covered by a rubber stopper, is obverted from the wind direction in order to exclude the effect of accidental gusts; in this test set-up the major portion of separated droplets is carried past the tube opening by the wind, and the relatively weak current of aspiration (10 cm per second) cannot deflect them from their path. Or the opening is placed more or less in the direction of the wind, in this case the droplets either bounce off the rubber stopper or are carried past the opening by the wind which blows at an acute angle, and only a few droplets can follow the aspirating current. The latter again carries all fine elements in the interior of the glass tube at about 4 mm per second without sedimentation through the entire tube (compare the tests described below). Only special accidents could cause settlement of isolated droplets on the gelatin layer.

1/ Fischer himself expresses a very cautious opinion towards the end of his paper: "Ocean air contains no germs transported from the land by air currents a certain distance from the land" (this journal, Vol 1, page 463). In the abstracts, on the other hand, the complete "sterility of ocean air" is invariably stressed.

Fischer recovered germs from the ocean air with openly exposed plates, whereas the aspiration tube remained sterile, usually when wind velocity and waves were strongest. These plate tests again do not furnish a correct picture of bacterial counts, since only a small percentage of droplets can precipitate from the currents which pass over plates at high velocities, at times with an upward direction.

Studies of the open air conducted on land, involving primarily dry dust particles, did not orient us properly about the germ content of the air and of the quantity of bacteria touching our bodies. These tests usually employ weak aspirating currents and recovery tubes opening upward, as in Petri's method; only a small share of particles present in the air can be recovered from strong currents passing across the opening. If the wet surface of a soil or clothing sample is exposed to a moderate air current until the fluid evaporates and sinks under the surface of the soil or cloth, all separation of germs ceases. As long as the material is still somewhat moist, even currents up to 60 m per second effect no transition of germs, even if the tests are greatly varied. In this respect the experimental data agrees with Naegeli's deductions.

On the other hand, separation may occur under certain circumstances after complete desiccation of the material. If the soil or cloth samples are dried in the air, the germs adhere to solid surfaces, and currents of 5 m and above fail to separate anything. When the rate is increased to 30 to 60 m per second, fairly strong transportation of germs occurs from dry soil containing fine particles; a current persisting for 15 minutes produced 40 to 70 colonies of prodigiosus. It is possible that the vibration of the tube, which is unavoidable at this velocity, causes the adhering mass to loosen and thus promotes transportation of small separated elements. If the dry soil is loosened artificially, currents of 5 m frequently suffice to carry off copious dust particles containing germs. This extreme value shifts according to the soil's composition.

Fabrics fail to liberate germs even at maximal velocities. However, sterilization causes them to become overheated and brittle, after which fibers and germs adhering to them separate and pass into the air. Again, if samples of cloth impregnated with prodigiosus are rubbed with another coarse piece of textile, a current of 5 m occasionally carries numerous germs onto the substrate. This did not succeed at all in the case of some textiles, particularly in the case of canvas.

A different behavior was shown by fine soil or dust scattered loosely on smooth or rough surfaces, glass, wood or cloth. In the case of very fine material, separation begins at a velocity of slightly above 1 m per second; a test with graduated velocities gave the following results:

(Dry dust with prodigiosus, a layer of 1 mm in a glass tube 17 mm in diameter. The air current was produced and graduated by means of an overflow flask.)

Velocity		Result
4 m	Velocity	= much prodigiosus
2.1 m	"	= " "
1.9 m	"	= " "
1.8 m	"	= " "
1.6 m	"	= several colonies prodigiosus
1.34m	"	= several colonies prodigiosus

Velocity		Result
1.3 m	Velocity	= several colonies prodigiosus
1.03m	"	= no prodigiosus
0.82m	"	= " "
0.39m	"	= " "
0.12m	"	= " "
0.05m	"	= " "

Coarser material required correspondingly higher minimal velocities for the transportation of particles. In tests with dry dust we never obtained complete removal of dust within the test period (15 minutes), neither from smooth nor from rough surfaces, not even with currents of 13 m. In the case of rough surfaces the reduction of dust usually was barely perceptible.

Under practical conditions a separation of adhering germs will be quite frequent. The required velocities usually exist in the open; various mechanical influences, including wagon wheels, pedestrians, etc., will cause isolation of small, loose particles; these are carried off by the wind. Transportation of finest dust begins at 1 m; at 2 to 3 m considerable quantities are transferred to the air. In addition to wind velocity, the angle at which it meets the surface is important.

Such currents which may cause removal of germs will not occur in closed spaces. However, vibration of the floor and instruments, as well as the friction to which clothing apparel is subjected during movement and handling, causes the agitation of quite considerable masses of dust and separation of fibers. This merely requires the persistence of suspended particles or their conduction through the air, and this, in turn, requires air currents of various velocity, depending on the particle size, in part velocities of surprisingly low rate.

It is important to point out again, as already done by Stern in the cited paper, that complete separation of germ-laden dust does not succeed even by means of strong winds, especially in the case of rough surfaces. Exposure of infected clothing to the air, or the "airing" taken by some physicians after a visit to a contagious patient, therefore does not produce the desired disinfection of clothing.

II. STUDIES OF THE MOVEMENT OF GERM-LADEN DUST PARTICLES AND DROPLETS INTRODUCED INTO THE AIR.

A. Movement of finest dry dust.

I had initially overestimated the currents which are capable of transporting finest dust, so that it required numerous futile tests until I arrived at the extraordinarily low velocities really involved here. Accordingly all previously used means for the production of air currents, such as bellows, water blowers, etc., were completely useless. As an example, a water blower was connected to a rectangular box (wooden frame with glass windows) 3.5 m long and 50 cm on a side by means of a tin connector; the tin connector was interrupted by a glass tube 8 cm wide, containing a Recknagel anemometer. Currents which barely moved the latter still conducted agitated dust through the box in spite of the considerable enlargement of the diameter and corresponding deceleration of the current.

In order to obtain graduated minimal velocities, the following arrangement was chosen: Thin glass points were attached to an overflow flask in order to obtain minimal overflow. The quantity of water flowing from each point per minute was determined, while the water column was maintained at approximately the same level. This produced calibrations between an overflow of 150 cc and less than 1 cc per minute. The hermetically sealed overflow flask was connected through a glass tube and hose to a small flask with a wide neck (capacity 50 to 100 cc), whose bottom was covered with nutrient gelatin and through which dust laden air was drawn at a rate corresponding to the outflow of water; it was then passed across the gelatin.

The flasks were sterilized; they were closed with rubber stoppers which had been submerged for a few days in sublimate solution and had been washed repeatedly in boiling water. The stopper had 2 holes; one was occupied by a short glass tube connected to the overflow flask, the other held a tube which reached down close to the gelatinous layer and had a right angle bend above. In order to prevent intrusion of dust, the bend had a slight flat deviation downward, so that the outer opening was only 1 cm below the horizontal part of the tube; in a few tests the downward portion of that bend had been lengthened to 2 to 10 cm. The lumen of the external glass tube was 10 to 11 mm. Small differences in diameter of the intake aperture and in the overflow of a certain tube were unavoidable; for these reasons the rate of flow, the time and diameter of the intake aperture were determined for each test and the rate at which the air entered the glass tube was measured.

The flask with the gelatin and the 2-hole stopper was closed by cotton wads in the glass tubes, sterilized twice in the steam autoclave and then stored for 4 days in a warm room; it was used only after the gelatin had remained free of colonies.

The tests were carried out in a separate room. Prior to commencement of each test a fine dust heavily impregnated with B. megaterium was distributed in the air by means of an atomizer used by laryngologists. The dust was made as fine as possible, partly by sifting, partly by forcing it through a bellows from one flask into another, partly by placing two layers of cardboard on the floor of a room filled with dense dust clouds, the upper one of which was removed after one hour; the lower one was then covered by extremely fine dust particles after several hours. Each batch of dust was tested for its content of viable megaterium germs prior to the experiment.

The first test series employed successive velocities of 84 mm to 2 mm per second; in all 15 tests the gelatin revealed a line of megaterium colonies on the gelatin several days later, which extended from the opening of the intake tube in the direction of the exhaust aperture.

These results suggest that entry of dust into the test flasks might be due to unavoidable manipulations, body movements and resultant air movement near the intake aperture.

For this reason the flasks with gelatin were subsequently placed in a larger box with glass walls, containing dusty air; every kind of vibration and air movement within this box were avoided. The box was 80 cm high and had a square surface 40 cm on a side. It had been hermetically sealed with putty and paraffin. The bottom contained a small door-like opening for insertion of the test flask; in addition there were a few smaller openings closed with a cotton wad or cork. One vertical wall contained two glass tubes, one above the other, to which rubber tubes leading to the overflow flasks were attached.

Prepared dust was atomized in this glass box one hour before the actual test started. The box was then closed and left motionless so that the great air currents caused by the pulverizer could no longer be influential. Two test flasks were then carefully placed in the box and their connecting tubes were attached to different overflow flasks. The box was again closed and ¼ to ½ hour was allowed to pass; now a wire leading out through the bottom, which was connected to the cotton wad in the bent intake tube, was pulled down with a careful rotating movement, removing the cotton stopper and opening the intake tube. This was done first with one, then with the other flask. The overflow flask connected to the first tube was now opened and dust-laden air from the box was conducted through the flask for 20 to 30 minutes at measured, calibrated velocities. The other overflow flask remained closed; the flask attached to it served as control to determine that accidental air currents produced by manipulation or otherwise had not carried dust into the gelatin bottle. If the gelatin remained sterile here, while the other flask exposed to slow air currents revealed germs, it was to be assumed that these had been transported by the air.

At a later stage of testing, where velocities were examined which were below those still sufficient for transport of dust, the control glass was used to aspirate an equal amount of air at a somewhat higher speed after termination of the test and to show by the development of colonies in this glass that the air in the box still contained germs and that the absence of colonies in the test glass could not be ascribed to lack of germ-laden dust. The following data illustrate the results:

Infection resulted at a velocity of	Infection failed at a velocity of
0.504 mm per second	0.094 mm per second
0.401 mm " "	0.106 mm " "
0.370 mm " "	0.111 mm " "
0.249 mm " "	0.129 mm " "
0.202 mm " "	0.141 mm " "
0.200 mm " "	0.167 mm " "
0.184 mm " "	0.204 mm " "

On the border between 0.18 and 0.2 mm per second infection succeeded at times, occasionally no germs were demonstrated. The range of this margin is apparently due to the fact that the downward deflection of the tube at which intake took place was not always exactly 1 cm. The influence of deviation from this downward bend becomes evident when the latter is arbitrarily increased. When the downward-turned glass tube was 3 to 4 cm long, the gelatin remained sterile at velocities of 0.245 mm, whereas infection occurred at 0.290 and at 0.417 mm; when the length was 6 to 8 cm, infection occurred at 0.334 and 0.345 mm, but failed at 0.280 mm.

Thus a horizontal movement of suspended germ-laden dust particles occurs through air currents of 0.2 mm per second; upward displacement by 6 to 8 cm occurs through currents of 0.3 to 0.4 mm per second.

These velocities are surprisingly low. I had not expected that the lightest elements of atmospheric dust involved here could still be impregnated so intensely with living and viable bacteria. Perhaps the dust used in these tests constitutes a very rare, selected material, so that these findings do not permit conclusions about practical conditions.

However, tests with dust materials show that particles laden with finest bacteria and carried through minimal air currents are not rare, and that they are attached to all dust in varying amounts. The results were identical with arbitrary indoor dust, but the duration of passage was prolonged occasionally, since the amount of dust particles in suspension was not as great as in the case of uniformly fine material. When I used clay impregnated with megaterium, in which separation of coarser particles had not occurred, I obtained a velocity of 0.243 mm per second and subsequent infection, whereas the latter failed at 0.218 mm. Short duration of passage in even stronger currents gave negative results, a sign that finest particles constitute a relatively small percentage of the dust. This percentage was even smaller in wood dust (from a barrel factory); but even in this case infection occurred after passage for ½ hour at 0.43 mm per second.

The fact that such fine dust particles transportable by very low air currents are widely disseminated is supported by the common experience that a fine dust gradually collects even in the interior of most cupboards and containers and in the most inaccessible places, which could only have been carried there by minimal currents. Heretofore it had been doubted that such dust is capable of transporting living bacteria. One can easily demonstrate that this is really the case. When the upper layers of such dust are carefully removed and placed on agar plates they invariably produce numerous germs, mold fungi and bacteria. A cupboard in a little-used room was thoroughly disinfected inside and the disinfectant was removed with sterile water; the cupboard was dried with sterile towels and kept closed for a few months; the dust collecting during this period contained considerable amounts of bacteria which in this case certainly did not originate with the wood or other sources, but had been carried there with dust particles through the smallest cracks and crevices.

If the smallest bacteria-containing dust particles are really as light and the air currents by which they are transported are as minimal as must be assumed after these tests, the dissemination of dust organisms to all possible areas of a closed room could be demonstrated on a larger scale, whenever specific and conspicuous bacteria are atomized.

Such experiments do indeed succeed and furnish proof for the enormous facility with which fine bacteria-containing dust can be transported to any point in a dwelling. Tests were carried out with dust impregnated with Bacillus prodigeosus. The test room was 5.40 m long, 3.50 m high and 2.40 m wide. The atomizer was placed in the middle, 1.16 m above the floor; a rubber tube led from the atomizer through a hole in the door to a bellows in the next room. After preparations were completed, about 20 agar plates were distributed in the room, partly in wire nets suspended under the ceiling and on the walls, partly on shelves, tables and on the floor. The plates were uncovered, the room was vacated and atomization was started. The atomizer hurled the dust visibly for a distance of about 20 cm in a horizontal direction; the dust clouds became diffused thereafter, a visible portion settled on the ground, the remainder became invisible. When half of the dust was atomized, the pulverizer was turned so that the current entered the room in the opposite direction. The room was entered 6 to 8 hours after atomization, the plates were covered and placed in the incubator. Four tests yielded the following numbers of prodigeosus colonies:

		I	II	III	IV
Plate 1.	Under the ceiling 3.30 m high middle of the room 1/	500	750	450	730
Plate 2.	At the same height as 1,	400	900	66	280
and 3.	off center	800	1200	520	660
Plate 4.	North wall 2.40 m	1000	1700	160	960
Plate 5.	North wall 1.50 m	1000	1500	100	1320
Plate 6.	South wall 1.0 m	300	800	2160	1300
Plate 7.	Floor near the south wall	700	600	1500	10000
Plate 8.	Floor near the north wall	750	800	3000	1350
Plate 9.	East wall above the window 2.70 m	0	0	38	208
Plate 10.	Floor, east wall under the window	0	850	--	3000
Plate 11.	South wall 2.70 m	120	700	134	350
Plate 12.	Floor, south wall, forward half	1500	350	2000	1900
Plate 13.	West wall 2.50 m	1000	2200	--	360
Plate 14.	Floor, west wall	800	900	3600	1600
Plate 15.	North wall, 1.60 m rear	300	1400	1000	1000
Plate 16.	Under the ceiling, 2.40 m, near south wall	--	--	780	600
Plate 17.	Floor, center	--	--	--	7500

1/ Compare the drawing page 207.

Accordingly the plates were thoroughly exposed to dust. Exceptions were seen in two instances, in the plates attached to the east wall above and below the window; during these tests a strong wind was blowing against the poorly closed window. Moreover, there were considerable differences in the dust distribution in the various tests. These were due partly to dissimilarities in dust material, partly to the fact that some tests were conducted with ventilation and others without. The influence of the latter factor will be discussed in more detail below.

An additional test with prodigiosus dust was initiated in order to counter the objection that air coming from the bellows had been responsible for the transport of all germs through the ventilated room. Atomization was carried out in the test room under a large cardboard box whose side walls had been carefully glued down with paper; the room was entered carefully 10 minutes after atomization, the paper strips were torn off, the room was vacated, and now, after a pause of the few minutes, the two halves of the box were carefully parted by means of strings operated at an angle from the next room. In this manner a significant air movement was avoided.

Unfortunately it was found later that the dust used by us contained fewer fine elements than that used in previous tests. Accordingly the major portion of dust had already settled on the bottom of the box after removal of side walls; only a small portion was still suspended in the interior of the box in the form of a dust cloud; for this reason we could expect only very slight seeding of all plates. Nevertheless nearly all plates showed colonies of prodigiosus:

Plate 1.	3.30 m High	5	Colonies	Plate 9.	East 2.70 m	4	Colonies
Plate 2.	Same	0	"	Plate 10.	East floor	2	"
Plate 3.	Same	2	"	Plate 11.	South 2.70m	1	"
Plate 4.	Not exposed	-	"	Plate 12.	Not exposed	-	
and 5.		-	"	Plate 13.	West 2.50 m	5	"
Plate 6.	South 1.0 m high	9	"	Plate 14.	West floor	78	"
Plate 7.	South floor	18	"	Plate 15.	North 1.60m	27	"
Plate 8.	North floor	39	"	Plate 16.	South 2.40m	5	"

Additional tests employing atomization of prodigiosus in the room were initiated to determine the time interval during which finest particles remain suspended in the air. The exposed plates showed quite copious growth 2 and 4 hours after atomization; they remained sterile after 8 hours.

The results of all preceding tests indicate that a portion of atomized bacterial material invariably consists of dust so fine it may be moved far away by air currents of less than 1 mm per second, and that they remain suspended in calm indoor air for more than 4 hours.

B. Movement of finest germ-laden droplets.

Preliminary tests showed that germ-laden liquid droplets may also be transported by extraordinarily low air currents. Droplets of a suspension of prodigiosus produced by sprays were conducted through the horizontal box 3½ m in length described previously. For control reasons, atomization occurred within a larger glass from which the droplets were carried away by an air current passing through it; droplets were conducted through a section of the box which was initially closed by sliding panes; this section was connected to the remaining space ½ hour after atomization by careful withdrawal of panes.

In an upright box with a surface of 20 sq cm and 1 m high, the plates exposed in the upper portion were all infected with prodigiosus, if suspensions were atomized in the described manner in a lower portion of the box and every perceptible air current was avoided.

A rain pipe 10 cm in diameter and 7 m long was attached to the external wall of the house; prodigiosus suspensions were sprayed below the opening or splattered on a solid surface by pouring; the air was aspirated at 5 mm per second at the other end; it yielded copious infection of all plates, and even 50 minutes after spraying germ-laden droplets were demonstrable in suspension within the pipe.

After these preliminary tests I expected low velocities, even lower than in the case of dust particles, in view of precise quantitative determination of air currents still capable of transporting droplets containing germs. The experiment was organized as follows: the glass box used in atomization tests was retained, as was the overflow flask with measured points of extreme thinness. The rubber hose leading to the overflow flask was connected in the box to a horizontally positioned glass tube with lumen of 1 cm, which was coated on the inside with gelatin. At the opposite wall the exit tube of the above-mentioned flask led into the box; a sprayer atomized the prodigiosus suspension here. Before the test the horizontal tube was closed with a cotton stopper; this stopper was removed with the wire hook not earlier than 20 minutes after termination of spraying. A control tube was attached next to the test tube; no air was aspirated through it. I usually passed 100 cc of air through the test tube. The tests gave the following results:

At 1.5 mm per second = the 15 cm long tube was strongly infected throughout its length, with the exception of the immediate proximity of the opening.

At 0.30 mm per second = same.
At 0.15 mm = same.
At 0.17 mm per second = sparse colonies along the entire extent of the test tube; the control tube is infected only at the open end.

Judging by results of the last test, such fine droplets moved by velocities of 0.07 mm and less are apparently present in very small number among the mass of somewhat larger and heavier droplets. In the following tests the test tube coated with gelatin was placed in a vertical position within the box; in other respects the arrangement was the same.

At 0.33 mm per second = the test tube 27 cm long is infected along its entire length; the control tube is sterile.

At 0.21 mm per second = the test tube 33 cm in length is infected to a height of 22 cm; the control tube is sterile.

At 0.10 mm per second = the test tube 16 cm long is infected lightly, but along its entire length. The control tube is sterile.

At 0.077 mm per second = test tube and control tube are sterile.

The last test gave the same result repeatedly so that the limit of upward movement of finest droplets produced by the spray was established a little below 0.1 mm.

In other vertically suspended glass tubes the results were not as distinct, since in these minimal air currents apparently forming without aspiration infected the control tube slightly. Tubes with a diameter of 1.5 cm yielded the following numerical data:

At 0.37 mm per second = test tube 27 cm long densely seeded along its entire length; isolated colonies in the control tube up to a height of 22 cm.

At 0.20 mm per second = test tube 20 cm long densely infected up to the end; isolated colonies in the control tube up to 12 cm.

At 0.10 mm per second = test tube 17 cm long rather densely seeded along its entire length, the control tube has scattered colonies up to 12 cm.

At 0.07 mm per second = the test tube is a little more densely and highly infected than the control tube; both show scant growth.

In order to determine the duration during which finest droplets protected against strong air currents remain suspended in the box, 1,000 cc of air were drawn through horizontal test tubes at a rate of 4.3 cm per second at various intervals after atomization. After 5 hours the test tube was still moderately infected in its entire length; no germs were aspirated after 6 and 12 hours.

We later made tests with germ-laden droplets analogously with those employing finest dust within the room, partly with and partly without ventilation. The room was the same as described above; a prodigiosus suspension was sprayed in its center at a height of about 65 cm, as before initially in a larger glass through which air was passed; later we used the cardboard box employed in the last test with dust. After termination of spraying it was elevated by a cord operated from without; in later tests I let the side walls drop down carefully in order to avoid greater movement of air. The cloud of germ-laden droplets contained in the box could only be distributed by minimal air currents present in the room. In the first, third and fourth tests we counted the colonies which had grown on the plates (this was done, as in the case of dust tests, by brief placement of the plate on sensitive celloidin paper in sunlight and by counting the colonies on the resultant photograph.). No count was made during the second test.

		I.	II.	III.	IV.
Plate 1.	Under the ceiling 3.4 m high, center of the room	-	Infected	1625	1200
Plate 2.	North wall 3.2 m, vertically suspended	39	"	134	27
Plate 3.	Same as 1, lateral	920	"	1820	1100
Plate 4.	North wall 2.4 m, vertically suspended	-	"	93	83
Plate 5.	Same, 1.5 m, vertical	8	"	147	42
Plate 6.	South wall 1 m	424	"	1281	2000
Plate 7.	Floor near the south wall	216	"	1890	3000
Plate 8.	Floor near the north wall	220	"	1920	2000
Plate 9.	East wall near the window, 1.9 m	366	"	1570	650
Plate 10.	Floor, east wall, under the window	240	"	1098	-
Plate 11.	South wall, 2.7 m, corner of east wall	304	"	976	750
Plate 12.	North wall, 1.5 m, vertical	-	"	121	74
Plate 13.	West wall, 1.9 m	424	"	2064	1800
Plate 14.	West wall, floor	312	"	1952	2400
Plate 15.	North wall, 1.6 m	564	"	1769	2700
Plate 16.	Center of room, 1.6 m	1200	"	1930	2600
Plate 17.	Floor, center	276	"	1500	-
Plate 18.	North wall, 1.8 m, vertical	14	"	153	41
Plate 19.	Same as 18	43	"	170	62

Thus strong seeding of all plates was seen in all tests. A smaller number of colonies were seen only on plates which had been suspended vertically on the walls, so that the bottom of the plate touched the wall. These showed strong growth only in their lower part; the form of growth showed distinctly that the overhanging edge of the glass plate had protected the upper part of the vertically hanging plate against droplets falling from above (compare figure 5). In several places within the room we had placed agar plates with the agar surface pointed down. All of these remained free of growth. Similarly to tests carried out in the box, we established the time after which germs containing droplets are removed from the indoor air. If plates were exposed 6, 7 and 8 hours after atomization and the air was purposedly agitated, all plates remained free of colonies. Since suspended droplets were still captured between the fourth and fifth hour, their persistence in air is about the same as in the case of finest dust particles.

Now that we had demonstrated that the finest droplets of fluids containing germs may be held in the air by very slow air currents and may be transported over very great distances, we may ask whether droplets transportable so easily can be produced only by a specially constructed spray or whether they may form under natural conditions during any kind of vaporization of germ-laden liquids.

This question is answered by some of the preliminary tests in which we atomized fluids. Supplemental tests were carried out in the room in such a manner that a prodigiosus suspension flowed through an opening about 2 mm in diameter into a dish 40 cm below. Agar plates were placed 1, 2 and 3 m's away in part below the ceiling. Although visible spraying of droplets could not be noted, with the exception of isolated larger drops scattered at the start, all plates were nevertheless covered with numerous prodigiosus organisms.

I attached the greatest importance and interest to the question whether droplets of oral and nasal secretions are formed and disseminated in such small and easily transportable form during speaking, coughing and sneezing. This is indeed the case. It is demonstrated most easily when the experimenter takes a small amount of prodigiosus suspension in his mouth and now speaks, coughs or sneezes, whether softly or loudly, and captures the disseminated droplets on plates placed at various distances and heights. Every instance of somewhat louder and more lively speech produces colonies on agar plates at a distance of several meters, even more so after coughing fits, while the plates remain sterile after very low and calm speaking. The dissemination of bacteria always present in the mouth secretion may be demonstrated by tests in a tightly closed, larger glass box. These tests are currently being carried out on a large scale in my institute, both with healthy persons and patients afflicted with such diseases as tuberculosis; Dr. Laschtschenko is trying to establish the extent to which such aerial transport, especially of pathogenic germs, is possible by spraying of mouth secretions in droplet form.

The dissemination of germs by finest droplets passed into the air and moved by the air has been underestimated heretofore. Germs may enter the air and be transported by it not only in the open, but also in dwellings at various occasions. In contrast to dust particles which contain germs, droplets may transport bacteria which do not tolerate drying and which for this reason have been considered exempt from aerial transport.

III. WHICH AERIAL CURRENTS OCCUR IN INHABITED ROOMS AND WHICH INFLUENCE THE DISSEMINATION OF DUST PARTICLES AND DROPLETS CONTAINING ORGANISMS?

The air currents found to be necessary for the transport of finest germ-laden particles and droplets can be evaluated properly only if the perceptible and imperceptible air currents usually present in dwellings and hospital rooms are measured and compared to the former. Of course, little is known about these conditions.

We normally measure only air currents which still register on a sensitive Recknagel or Fuess anemometer. The limit of sensitivity of these instruments is near 15 to 20 cm per second. Dynamic instruments which are twice as sensitive may be constructed of very light materials such as feathers, windmill vanes made of straw and tissue paper; to better advantage one uses static anemometers consisting of a square plate made of a frame of straw stalks covered with tissue paper and attached to a long straw which is balanced on its upper ends by a small counter weight and which has an axis passing through horizontally which moves on glass bearings with as little friction as possible. The tissue paper plate is deflected at velocities of 5 to 10 cm, sometimes even below 5 cm per second.

We are unable to feel lower velocities. I have carried out a few measurements without intending to treat the subject extensively. Too many factors are involved -- the skin area, moistness of the skin, individual sensitivity, the diameter of the air current, the temperature and humidity of the air -- so that determinations of constant relations encounter great difficulties. I have chosen the region of the internal corner of the eye as particularly sensitive; I have also varied the diameter of impinging currents and air temperature. The various velocities were produced by a large graduated gasometer made of tin into which water flowed at different speeds through variable openings. A rubber tube was fastened to the upper conical end, which was in turn attached to a glass tube; the opening of the latter was carefully brought to within a few cms of the test person's eye to determine whether the outflowing air current was felt as such. The temperature of the water and of the air in the gasometer was kept constant in every test; in tests with cold air the person sat in a warm room and the outflow tube for air was passed through a door. I obtained the following values: (see table).

TABLE OF PERCEPTIBLE AIR CURRENTS

a) At a temperature cf 25°C:

Diameter of Air Stream 95 sq mm	Diameter 219 sq mm	Diameter 415 sq mm
16 cm velocity = distinctly felt	26 cm = distinctly felt	16.4 cm = distinctly felt
15 cm velocity = just felt	15 cm = just felt	13.5 cm = partially felt
14 cm velocity = only partially felt	11 cm = partially perceived	10.5 cm = in some cases still felt
11.3 cm velocity = usually no longer felt. A few cases of questionable data	8.2 cm = no longer felt	6 cm = imperceptible
10.6 cm velocity = not felt		
8.6 cm velocity = not felt		

b) At a temperature of 15°C:

Diameter 19.6 sq mm	Diameter 95 sq mm	Diameter 219 sq mm	Diameter 415 sq mm
28 cm = still positively felt	18 cm = positively perceived	13 cm = distinctly felt	12 cm = still positively felt
20.5 cm = felt only after prolonged exposure	13 cm = distinctly felt in sensitive places	11 cm = still positively perceived	10 cm = occasionally fistinctly felt
18 cm = questionable data	10 cm = isolated correct responses	9 cm = uncertain information	8 cm = imperceptible
14 cm = only isolated correct information	8 cm = imperceptible		
11 cm = imperceptible			

c) At a temperature of +3°C:

Diameter 19.6 sq mm	Diameter 95 sq mm	Diameter 219 sq mm	Diameter 415 sq mm
13.5 cm = distinctly felt	17.8 cm = very distinct	15 cm = very distinct	12 cm = very distinct
8.5 cm = uncertain	4.2 cm = still positively felt, always correct responses	8.4 cm = distinctly felt	8.3 cm = distinctly felt
	2.9 cm = imperceptible	3 cm = usually correct responses	4 cm = just perceptible
		1.2 cm = imperceptible	2 cm = very weakly felt, frequently uncertain information

A certain diameter is necessary for the perception of an air current, probably because few nerve endings are affected by a smaller diameter. Aside from this the temperature of the air current is an important factor; perceptibility increases with lower temperatures, slowly upon a drop from 25 to 15° and very considerably during continued decrease to +3°, so that air currents with the latter temperatures were felt at a velocity 3 times slower than at 25°.

If the average temperature is maintained at 15°, the limit of perceptibility for air currents is near 10 cm per second. Compared with velocities determined above, which suffice for the transport of finest germ-laden dust particles and droplets, the velocity of a just perceptible air stream is about 1,000 times greater; the air velocities still demonstrable with the most sensitive anemometers occupy approximately the same position.

Consequently it is very difficult to find a feasible yardstick for those minimal air currents which always occur in the interior of our dwellings and which are available for the transport of atmospheric germs. I have tested, without success, the various methods for observing minimal air movements, as earlier done by Lang and Wolffhuegel (Zeit. f. Biologie, Vol. 12). Smoky wicks and ammonium chloride vapors seem to be the most sensitive testing agents, but I have not been able to date to use these in a practical manner with quantitative graduation. The deflection of candle flames has proved itself to a certain extent in the measurement of such air velocities which still cause perception of draft, but which far exceed the velocities normally present inside a dwelling. The candles chosen for this purpose have a thin wick and a wide flame, so that the latter has relatively weak adhesion to the wick. Small paraffin candles, as used on Christmas trees, are most suitable. They show distinct deflection of the flame at 5 to 10 cm per second and they serve to establish the presence of air currents causing "drafts," even without the presence of sensitive persons. If numerous candles of this type are distributed in a vigorously ventilated room, deflection of flames is seen near the vent openings and in the direction of the strongest ventilation currents; most flames placed further away from the current show no movement.

The air currents present in the inhabited portion of a closed room, whether ventilated or not, generally are considerably slower than those still perceptible. Strong currents are produced in a closed room only at the entrances and exits of air currents, by walking and manipulations, as well as by breathing. Near a window or a vent opening, near a poorly insulated point at the window or door which is exposed to the wind, the velocity may reach 0.5 to 1 m per second or more; the air is placed into similar or occasionally even faster movement by walking and manipulations; during breathing the air currents measure 2 m per second or more immediately at the nasal opening. All of these velocities decrease very rapidly with the distance from the current's point of origin. If the air is distributed uniformly from a vent throughout the entire space, the velocity soon decreases 100-fold or more. Assuming that the admitted air stream passes through a room at nearly equal distribution throughout its diameter, and that the air in the room is renewed three times in one hour, the result is a median velocity of 4 mm per second along a path 5 m long; since ventilation in practice usually renews the air only 1 to 1½ times, we usually may assume a median velocity of only 1 to 2 mm per second in the interior of dwellings. In the absence of ventilation facilities, equal inner and outer temperatures and calm winds, these values certainly will drop even more, as low as 0.5 m and less.

Consequently the effect of air currents present inside a dwelling on dust particles and droplets must be such that the finest sizes used in my tests are still transported under all conditions, while the currents do not suffice for the movement of coarser elements.

In the case of dust and droplets produced by spraying, the various fractions must be differentiated according to size and weight. Coarser particles and droplets usually predominate; this is shown by several experiments described above and especially by tests made in my institute earlier by Stern. Stern found that the air rapidly loses its germ content in a calm room after agitation of germ-laden dust. More than 90% of arbitrarily chosen interior dust settled during the first 5 minutes; the air was nearly sterile after ½ to 1 hour. About 3/4 of atomized germs settled out during the first half hour in the case of selected dust. Stern noted further that a movement among such agitated germ-laden particles occurs to a higher degree only upon 7-fold renewal of the air; 15 minutes later the germ contents was nearly zero, and 20-fold ventilation removed almost all organisms after 2 minutes. In this case air currents of about 3 cm per second and of 10 cm and more near the vent opening acted on particles in the center of the room; such currents apparently are capable of transporting coarser dust, which constitutes the major share of every kind of dust, horizontally and upward. On the other hand, removal was not effected by 3 to 4-fold renewal of air; gradual settlement proceeded approximately in the same manner as seen in completely calm air; i.e., the currents usually present in the interior are unable to influence the germ-laden dust consisting in the main of relatively coarse elements.

Finest particles are easily transported by all currents found in dwellings. These currents have a velocity 10 times greater than is necessary for the movement of very light particles, even in the case of minimal ventilation. This fraction of dust is not only agitated where ventilation passes through the room but is subject to gentle motions and eddies produced by pressure and displayment of air molecules, which are strong enough to distribute particles outside of the range of the ventilating current. Even in a completely ventilated room, the air is kept in motion by unequal temperatures existing on the borders of the room and by minute air currents penetrating through poorly insulated places in windows and doors; this current is large enough to transport germs in the form of very small particles and droplets.

Heretofore we have been unable to measure or visualize this type of current. It is possible, however, to distribute minute droplets or particles charged with specific organisms in the air of a dwelling, to capture them in various parts of the room and to count the germs deposited on each plate. The tests described on page 195 and 199 offer a good idea of minute air currents present in a closed room and of the changes which are brought about by specific ventilation. Tests 3 and 4 with particles and 3 and 4 with droplets, as discussed on page 195 and 199, were carried out in short succession in the same room; test 3 was made without ventilation, test 4 with ventilation which renewed the air 3 times and in which the air entered through a Sheringham valve installed in an upper window pane, while the air left the room through a square opening of similar diameter in the floor in the southwest corner of the room. The latter led to a chimney in which a Bunsen burner of large caliber produced strong aspirations.

Figure 1. Experiment with droplets without ventilation.
Figure 2. Experiment with dust particles without ventilation.
Figure 3. Experiment with droplets in the ventilated room.
Figure 4. Experiment with dust particles in a ventilated room.

Droplet experiment 3 without ventilation, as depicted in the drawing, produced extremely uniform distribution of germs; a slight accummulation is noted near the door, which suggests that the general direction of air was east to west; the difference in the number of colonies is almost within the margin of error, so that a nearly undisturbed circulation of air strata enclosed in the room had existed without strong influence from the outside.

Test 3 with dust particles is different. On the day in question there was a stong easterly wind playing on the poorly closed window; the door in the west wall led into a hallway which communicated with other open rooms and the staircase. The distribution of organisms clearly shows that an air current coming from the window takes a generally downward course, although part of it is distributed upward and fills the long axis of the room until it passes as a wide current through the door into the hallway.

The picture is quite similar in the test with droplet atomization and ventilation, corresponding in the main to the direction of the ventilating stream. However, the changed position of the exit opening produces marked deviation. Whereas in the previous tests the main current passed primarily along the north side of the floor (since the hallway was open towards the north), the current now dipped down along the south wall toward the vent opening and settled there. It is quite evident that the entering air stream is initially deflected against the ceiling by Sheringham's valve. The plate attached below the portal of entry contains only 650 germs; that suspended in the southeast corner only 750 germs; they had not been in the path of the actual current, but had been touched only by side currents and eddies.

Test 4 with dust particles utilized even stronger ventilation (full flame of the Bunsen burner). Here the path described by the air due to ventilation is most evident. The current is not effective above the inlet, directly on the wall, nor does it reach the upper southeast corner. Considerable dissemination takes place toward the ceiling, covering plates suspended here with 600 to 1000 germs; on the opposite side of the room only fractions of this upper stream are influential (360 colonies above the door); the main portion of the entering air is carried with great energy downward and toward the south wall as far as the exit vent. The high accummulation of germs under the window may be explained by the impaction of this stream against the floor and its subsequent distribution towards the east. In addition, the large fraction of coarser particles in the dust probably shares responsibility for accummulation of germs over the entire floor, since these settle rapidly after atomization.

Thus experimentation with particles and droplets charged with specific germs offers quite instructive pictures of the direction, distribution and intensity of air currents within a room. If an attempt is made to obtain similar results with smoky, ammonium chloride, etc., one soon recognizes that observation is limited to such a short duration and is so incomplete that no clear picture can be obtained. Tyndall's method of visualizing particles by light rays or Aitken's dust particle counts are not as practicable for analysis of enclosed air spaces. Moreover, they include even the finest elements of dust, which do not necessarily carry and transport living organisms, so that their results do not permit hygienic conclusions.

The bacteriological method offers a detailed perspective, according to requirements, in the number of exposed plates; it also yields results in the form of documents produced by exposure of plates on celloidin paper. I believe that some problems involving the ventilation of dwellings may be approached by this method.

The droplet method is recommended for future tests. It is easy to obtain droplets of uniform size during the spraying of liquids; in the case of dusts the fraction of fine and coarse particles is too variable. The preparation of dust is also far more cumbersome and time-consuming than the production of a prodigiosus suspension suitable for atomization.

Aside from the count of colonies on dust plates, an idea may be obtained of the direction of the air current from distribution of colonies on the various plates. This effect was particularly distinct on vertically suspended plates which show the gradual precipitation of air and the protection offered by the upper glass lip (a reproduction of photographs of 2 such plates diminished to 3/5 their size is shown by figure 5; the plates were marked with arrows on the outside, which pointed to the floor after attachment. The colonies developing in the upper portion of the plates are larger than those further down only because the growth of prodigiosus is inhibited when colonies are too dense).

We did not succeed in getting similar pictures on horizontally placed plates. The plates were oriented by arrows so that the original position of plates could be restored after cultivation. In some tests two plates were positioned on every spot; each was turned 45°, one towards the window and the other away from the window. In another test small slanting roofs of paper were installed which were designed to protect the plate against an air current from a known direction. Strong and constant deviations were not seen, occasionally there was a slight indication of a direction of flow. The air currents in question here are probably too weak and too irregular to produce a certain direction during a test lasting for several hours. At any rate, experimentation should continue in this direction.

Finally, if we consider the effect of ventilation on removal of germ-laden particles and droplets, as reflected from a comparison of data from tests 3 and 4, it is found to be unexpectedly small. The plates under the ceiling, in distant corners, etc., are certainly not protected by the vigorous ventilating current passing through the room; all of them received a large share of germs. The side currents and eddies forming near the ventilating current produce general dissemination of germs under all circumstances.

If atomization is not repeated, ventilation produces sterile air or nearly sterile air more rapidly than in the absence of ventilation. This was demonstrated by a few tests with and without ventilation in which equal quantities of the same dust were scattered in the same time interval, although exposure of plates was started 4 hours after atomization. These plates showed:

	Without Ventilation	With Ventilation
At a height of 0.97 m	310 Colonies	15 Colonies
At a height of 1.60 m	150 "	14 "
At a height of 1.80 m	432 "	12 "
At a height of 2.10 m	480 "	9 "

Thus ventilation had removed a very considerable part of the dust within 4 hours. This result applies only to dust particles of selected fineness. Under natural conditions, as in a sick room, germs adhere primarily to coarser particles which, as demonstrated by Stern, cannot be removed by the customary ventilating currents. Moreover, the efficiency of ventilation and the danger arising from fine particles appears in a different light when it is remembered that dust droplets are produced incessantly under natural conditions. The disinfecting effect of ventilation on the air of dwellings and hospital wards is thus very small. Only a fraction of germs introduced into the air can be removed by ventilation in the most favorable case; the organisms spreading into parts of the room not reached by the ventilation in the form of fine droplets and particles, as well as those temporarily introduced to the air in the form of coarser particles and finally the deposit of light and heavier dust descending on all surfaces, all this involves a very considerable danger of infection which overshadows the organisms removed by ventilation.

IV. CONCLUSIONS ABOUT THE MANNER IN WHICH PARASITIC DISEASES ARE SPREAD, AS REFLECTED IN THE PRECEDING RESULTS

Since the velocity of air currents required for the transport of bacteria-laden, finest particles have been largely overestimated, and the significance of liquid droplets for the dissemination of germs through the air has been neglected, it must seem desirable to revise our concepts of the dissemination of contagious diseases on the basis of results discussed here.

Contagious diseases were heretofore classified into two groups according to their natural manner of dissemination. To the first belong the acute exanthems which for a long time had been called diseases with open "volatile contagion," especially smallpox, measles and spotted fever. The volatile nature of the unknown contagium has been inferred from these diseases, because isolation of patients and other precautionary measures are usually unable to control the epidemic focus, because nurses and physicians are easily infected and because a brief stay near the patient, without actual contact, usually produces infection. Among other pathogens the bacillus of tuberculosis has been recently recognized as an airborne, volatile virus, since its viability in completely dried and pulverized tubercular sputum has been demonstrated, and because the genesis of tuberculosis most probably is attributable to the inhalation of TB bacilli.

The second group is formed by diseases with non-volatile pathogens. The method of dissemination differs from the first group by more difficult infection; prolonged association with the patient, common use of utensils, contact with excretions, beds, clothing, etc., is necessary for transmission. Contacts, eating and drinking, and insects may transport the contagion, but not air currents; a short stay in the sick room without contacts, or presence in the neighboring rooms without common use of utensils as a rule does not lead to infection. This is the case also with cholera, and Koch has found the cause of this type of dissemination and non-volatility of the pathogen in the property of the cholera bacillus to die upon drying. The same property was found in the pathogens of influenza and pneumococcus; it is assumed correctly that air transmission occurs only by contact with fresh excretions. Typhus, diphtheria, glanders and suppurations also belong in the category of non-volatile diseases on the basis of accummulated practical experiences. Effective isolation is relatively easy; transmissions from which contacts with sources of infection can be excluded are not known. In some cases with a completely obscure etiology one has assumed transmission through the atmosphere; this concept is supported by the results of experiments in which the strong resistance of typhus bacilli and the tenacity of diphtheria bacilli in their dry state have been demonstrated, so that they seem capable of existing in dry dust. On the basis of such experiments diphtheria, typhus, etc., have recently been recognized as diseases with volatile pathogens.

The grouping of contagious diseases should proceed according to the following points:

Firstly: An atmospheric infection in the form of fine droplets separated from liquid sources of infection may occur in connection with all contagious diseases, although to very dissimilar degrees. Occasionally an atmospheric transmission in this form must be possible even in the case of cholera, as during the breaking of waves in a diseased harbor by means of steamship wheels on an infested river, or in dwellings during the washing of laundry contaminated with excretions and by similar means. Similar transmissions may occur in the case of typhus; the epidemic in Helgoland described by Mewius (this journal, Vol. 23) may have developed due to droplets passing into the air from sprays emanating from sewers. At any rate, aerial infection in the case of these diseases must take second place to other modes of transmission; special local conditions, accidents during the manipulation of infectious material, contribute to exceptional atmospheric infections. Contacts, eating and drinking are the actual and preferred modes of transmission.

A far greater danger of infection is presented by droplets hurled into the air in infectious diseases of the throat and the respiratory organs connected with coughing and sputum. The passage of pathogens into the air in droplet form must be a frequent occurrence in diphtheria, tuberculosis, influenza, whooping cough, pneumonia as well as plague connected with pulmonary affection. Judging by the tests described above, one cannot doubt but that every kind of coughing, sneezing and shouting will conduct copious amounts of such droplets of sputum and mouth secretions into the air, and that these spread far into the room and remain suspended in the air for long periods of time. The objection that the mucous covering in which the pathogen is usually excreted hinders such spraying and dissemination is not valid. In pharyngeal diphtheria the bacilli have been demonstrated throughout the liquid which coats the mouth, which is very easily reduced to fine droplets; but in the case of tuberculous sputum, numerous experiments have shown that various test animals are easily and positively infected through inhalation of moist atomized material.

Koch has also taken account of this path of infection in the transmission of human tuberculosis. He writes in 1884 (The Etiology of Tuberculosis, Reports of the Imperial Public Health Service, Vol. 2, page 79) "It may be assumed that a healthy person accidentally in the presence of a tubercular patient will be infected if he inhales freshly expectorated particles of sputum propelled into the air." Koch adds, however, that "such an infection presumably does not occur too frequently, since sputum particles are usually not so small that they remain suspended in the air for longer periods of time." The necessity for a direct approach of patients by healthy persons and the brief persistence of droplets in the air are questioned by investigations discussed here, suggesting the possibility that this type of transmission is more significant in tuberculosis than heretofore assumed. Direct tests with tuberculous sputum must establish whether droplets produced by vaporization are as easily transported as those from prodigiosus suspensions, or less easily. Dr. Laschtschenko is conducting tests of this type. He has already obtained positive results; that certain quantitative differences will be found is already indicated by the ease with which test animals are infected when subjected to inhalation of atomized sputum; and that different behavior cannot be expected from such mucous material, that at least the thin fraction of the excretion, which also contains TB bacilli, is divided into minute droplets during vaporization, as are the other suspensions containing bacteria. Heretofore the dry and pulverized tubercular sputum has been considered universally dangerous. There is no valid proof of its ability to cause infections; animal tests with inhalation of dry pulverized sputum have always failed, although sputum dust was injected subcutaneously and intraperitoneally. In order to explain this peculiar effect one may assume that bacilli which are very resistant to drying nevertheless lose part of their viability at the degree of dryness required for transportation on minute dust particles, so that they require prolonged resting for their settlement and initial proliferation, and for this reason are usually eliminated from the respiratory tract before they are solidly established. One could assume that test animals have better defenses against inhalation tuberculosis than man, an assumption which can hardly be sustained in view of the prompt effect of inhalation experiments with vaporized, moist sputum.

In those diseases of the respiratory organs, in which the pathogen does not survive drying and for this reason cannot occur in the air on particles, inhalation of vaporized droplets of secretion is undoubtedly a frequent and dangerous mode of infection, perhaps the most dangerous. It competes only with contact infection: contact infection may be preferred wherever numerous possibilities are present, as between the patient and the caretaker who deals constantly with the patient, his laundry, etc. In the case of persons who approach the patients only temporarily, as during the visits of influenza patients or a brief meeting with an influenza patient elsewhere, it is most probable that the pathogen is transmitted through droplets of sputum propelled through the air. This mode of infection is particularly dangerous in the diseases mentioned because the pathogen is brought into the respiratory tract and reaches the point of invasion through which the morbid process is established.

Aerial infection through droplets of excretion must be paid more attention in the future. Nevertheless, the possibility of such atmospheric infection is not identical with "Volatility of the contagium." Transmission through droplets is not as dangerous as aerial infection by means of dust particles.

It is true that germ-laden droplets of smaller caliber are not separated rapidly from the air; part of them has been found to remain suspended in calm interior air for up to 5 hours. However, this is followed after some time by a period in which all droplets have made contact with some surface, such as walls, furniture, floors or the surface of the human body. The small droplets dry rapidly and the accompanying germs are solidly fixed so that separation by air currents does not occur. This is clearly evident from separation tests described on page 187. Mechanical friction with the dried mass may produce particles which may reintroduce germs to the air, but this will be an exceptional case.

In the case of aerial infection with droplets, the contaminated habitation and the sources of infection exported from it do not constitute a persistent menace, but only the excretions hurled into the air by the patient at the time or several hours ago.

In spite of extensive distribution of organisms through the air in the form of droplets, chances for infection are very small in the open. Minute droplets from an aerial source of infection must soon be infinitely diluted by the constant supply of fresh air, so that absorption of such isolated germs by inhalation or contact constitutes a curiosity no longer debatable from the hygiene viewpoint. The atmosphere must really be "free" and nothing should impede the lively exchange of air in the open. Narrow streets, enclosed yards and housing projects are only partly accessible to the protective influence of diluting air masses. One should take great care in placing infectious wards at some distance from other structures due to the real possibility of atmospheric infection. Under certain conditions the danger of infection may exist even under the free influence of the wind; for instance, if the wind carries particles or droplets for some time from the source of infection in the same direction toward exposed dwellings. The typhus epidemic observed in Helgoland by Mewius gives an example of such a possibility, although it is not clear whether infection took place through direct inhalation of vaporized droplets or by contact with portions of the dwellings which had been contaminated by numerous droplets.

Secondly: In the case of aerial infection with dry particles one should differentiate between coarser elements carried by air currents moving at 1 cm per second and faster, and minute ones transported by currents of 1 to 4 mm and less. Very infectious materially is occasionally separated in the form of coarser particles and transported over short distances by strong air currents; these may carry living germs which are very susceptible to complete drying. Separation in a living space is due not only to air currents;

this would require currents with velocities over 5 m. However, simultaneous mechanical agitation (beating, brushing of clothes and beds, etc.) may nevertheless produce separation of many coarser particles. Their transportation within the room requires air currents of at least 1 to 2 cm per second. According to Sterns' experiments, separation of large amounts of vaporized germs commenced only at these velocities; the coarsest elements were not affected by such currents. Moving persons and intakes and outlets of air produce even higher velocities in living spaces, but these are of short duration. A germ-laden, separated particle of greater size may be transported for a short distance if it encounters such currents, but the velocity soon drops, the particle falls into air layers with less movement and settles to the ground. Repeated ascent is possible under particularly unfavorable circumstances. We must not visualize these particles as being suspended and circulating in the air for any length of time; they exist very briefly and over a short distance as an aerial particle, and they may change their location without increasing the dangers of infection. They do not present a specific source of infection when compared to germs absorbed by contact. They also adhere to the infected room or location at which sources of infection arise; they are not carried to neighboring rooms by the air (aside from artificially constructed oddities); the persons present in the room are not specifically endangered by the short-lived suspension of isolated particles; the danger is the same as if germs had settled out of the air and had not yet been reintroduced. Occasionally absorption of such particles from the air is merely a subordinate category of contact infections. If one speaks of aerial infection when living pathogens are transported by strong air currents in the form of coarser particles, all contagious diseases will have a volatile contagium. Hesse has demonstrated occasional precipitation of germ-laden particles in the case of cholera bacilli, and Williams showed in my institute that a vigorous air current will transport living cholera bacilli from a mixture of clay and bacilli to a nutrient substrate. The greater danger of dissemination represented by diseases with volatile contagium would be obscured if such aerial transport is considered "volatility" of the contagium.

The hygienically significant difference between volatile and non-volatile contagia is based on the dissemination of the pathogen in the form of minute dust particles which are transported by ubiquitously present and effective air currents of less than 1 to 4 mm per second. Once they are introduced to the air, they remain suspended for hours; they follow the smallest air movements and spread into neighboring rooms. Although they settle occasionally, this does not mean that they have finished playing their part; being deposited loosely on various surfaces, they are whirled up due to different causes and are resuspended in air. The air currents produced by walking, by arm movements, by breathing or during the opening and closing of doors are strong enough to separate these particles from nearby surfaces and to carry them through the air for some time, provided they are sufficiently small and dry. The sources of infection inherent in such particles endanger the spaces into which they are introduced for longer periods, even if the patient is no longer present and the production of infectious germs has long ceased. In addition, they may be taken from the sick room with various utensils, clothing apparel and beds, after which they are transferred to the air in other rooms and menace even those persons which had no direct contact with the patient or his items. In atmospheric organisms we find a sustained specific possibility for the dissemination of germs which develop separately from contact infection and proceeds along special paths.

The question whether volatile contagium is formed in a certain disease depends on the circumstance whether the pathogen in question remains viable in the form of such minute, easily transportable, dry dust particles. This question cannot be answered by tests designed to determine how long and under which conditions the pathogen tolerates drying without being destroyed. Nor can the answer be expected from experiments in which bellows are used to produce very strong currents which do not occur in practice, which are then conducted through a dust mixture with dried pathogens. Under such conditions even cholera bacilli may be vaporized while still alive.

Only such experiments are decisive in which air currents of 1 to 4 mm per second are directed on agitated dust impregnated with pathogens, which is then captured and tested for viability after travelling 1 m or more. If these tests have positive results, the pathogen may occur in the form of a dry volatile contagium which hovers in the air for some time, is easily transported and thereby renders the air specifically dangerous.

Dr. Neisser of our institute is presently conducting tests to determine the air currents by which various pathogens are still moved upward or horizontally over varying distances. According to his results, most pathogens are much more vulnerable to the degree of dryness required for minute, easily transportable particles than Bacillus prodigiosus or Bacillus megaterium. The slow currents which still move these bacilli in a living state can no longer transport diphtheria bacilli, although the latter may be carried along for a short distance at high velocities. Dr. Neisser will soon report his numerous comparative experiments.

Even in the case where a pathogen has been shown to move in air currents occurring in dwellings, it may not be classified under "volatile" contagia on this basis. This does not furnish information about the extent and activity of other means of transportation for this contagium. If the majority of transmissions occurs through contacts, eating and drinking, an exceptional absorption from the air may be practically unimportant. The formation of such minute particles, as would be required for the volatility of a contagium, is very difficult under practical conditions. The excretions must be dried on smooth surfaces and then finely ground, but this rarely produces particles of the required size and weight. They may also be dried on porous material, on clothing, floors, etc.; in this case they are occasionally separated with fibers and soil particles, but usually they form relatively heavy particles which soon settle out. If the acute exanthems reveal the distinct volatility of the contagium with its sequences, this is probably due to the fact that dry and small particles of the contagium are separated here with special ease. Various movements and the friction against clothing causes particles to separate from the dry, brittle skin of the patient, which may continue their existence as fine aerial particles. In the case of pathogens reaching the air in the form of mucous and aqueous excretions, the formation of minute, dry aerial particles must be far more difficult. Consequently the acute exanthems constitute the only contangium volatile in the dry state; in addition, aerial transport of pathogens may occur when sputum or nasal secretions, etc. are reduced to droplet form. Here aerial infection constitutes one of the most frequent and important paths of infection.

Perhaps TB bacilli may also spread in the form of dry particles; we do not know the extent of this action. The inhalation of droplets expelled during coughing must be a more important factor. Aerial infection through droplets may be a factor in the case of influenza and whooping cough. Infection through the air is not a factor in connection with pathogens that do not occur in the form of minute, dry particles and which are not given off in droplet form. These include cholera and abdominal typhus; it is well known that such patients may be placed between other persons without danger of infection, provided contacts are avoided. Contact infection should certainly dominate in diphtheria, and most transmissions are traced to direct contact with the patient, to eating and drinking utensils, handkerchiefs, toys, etc. There may be isolated cases in which complete and immediate disinfecting treatment of excretions, dirty laundry, eating and drinking utensils has been carried out and where the disease was acquired through mere presence in the sick room. Even in such instances a contact infection is difficult to exclude; here the possibility of expulsion of droplets must be considered, especially if restless and crying children, patients with stenosis, labored breathing, and coughing attacks are involved.

A special mention should be made of wound infection, especially of the danger of vaporized droplets of excretion during aseptic operations. Many surgeons have noted in the last few years that suppuration and sepsis set in, in spite of all precautionary measures. The cause of such mishaps is not clear. Inadequate disinfection of the hands has been blamed, and all attempts to improve this situation have been unsatisfactory. The air has been considered a factor, since it had originally figured on an equal basis with contacts in Lister's method. Only dry germ-laden particles had been considered as a source of possible infection.

On this basis the air in the operation room was cleared of dust, persons occupied there were given sterilized gowns and protective shoes, the floor was moistened, etc. The amount of dry germ-laden dust particles in the air of operation rooms has been determined repeatedly and with contradictory results. Such analyses offer few reliable conclusions. The most important pathogenic germs cannot be grown on agar plates or in Petri filters after capture; these include the streptococci, diplocci, coli types, etc. The organisms settling on exposed plates originate from completely dry particles containing viable bacteria which are usually saprophytic, thus offering no clue to the infectivity of the air. The number of wound pathogens remaining in the air in the form of minute dry dust particles, which infect solely through the air, is very limited. Actually only Staphylococcus pyog. aureus and albus tolerate such drying. Under practical conditions these bacteria have no chances to transfer to such small and dry aerial particles. The above-mentioned cocci are rarely captured from the air; if air analyses disclose Staphylococcus pyogenes aureus and albus, this has usually been found in the absence of tests which positively identify yellow or white cocci as these pus-forming strains. The air contains numerous cocci which grow similarly on agar and which apparently have no relation to those pus-producing organisms.

It is more likely that aerial infection of surgical wounds is caused by droplets of oral and nasal secretion expelled by the assembled persons during speaking, coughing and sneezing. The oral secretion of healthy persons frequently contains Staphylococcus pyogenes aureus; Diplococcus lanceolatus is found just as often; during the smallest pathogenical changes of the pharyngeal membrane we find massive streptococci; decaying teeth are a storehouse for all more or less questionable bacteria. Thus we find dangerous pathogenic strains here which are not attenuated by drying, but retain their full virulence as shown by numerous animal experiments.

The expulsion of such droplets may come from the surgeon, from assisting personnel or from observers. The danger increases with the number of persons present who speak loudly, cough or are infected with catarrh. A certain spatial distance from the operating table helps very little. A large portion of expelled droplets may be carried for several meters by minimal air currents and may land on the surgical area or on the instruments which usually are exposed. The patient himself represents a considerable menace; his irregular, heavy breaths under chloroform anesthesia may propel his own oral secretion and infect the surgical zone.

Excessive moistening of the floor in operation rooms may involve more danger than dry dust if the water is splattered during walking.

In my opinion the majority of wound infections is caused by contact, and these have been considered by the surgeons to be more important than aerial infections. However, we must not ignore the danger represented by droplets of excretion introduced to the air in operation rooms; we must count on the possibility that certain abnormalities in surgical wounds protected against contacts are attributable to this heretofore neglected mode of infection.

Since it would be fruitful to determine the extent of these infections in comparison to other modes endangering surgical infections, and since such questions can be decided only when applied to practical conditions, I have asked Professor Mikulicz to join me in applying the processes studied by me experimentally to sources of error inherent in modern asepsis. Professor Mikulicz has agreed, especially since he had dealt with these questions for some time. Together with our assistants we have already attacked numerous individual projects and we hope to publish detailed data on the sources of error in asepsis and on the means by which they can be prevented.